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THE X-20 FLIGHT CONTROL SYSTEM DEVELOPMENT

EDWARD H. McDONALD
JOSEPH A. FARRIS

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SYSTEMS ENGINEERING GROUP
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
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Program 620

NOTICES

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FOREWORD

This report was prepared after the termination of Program 620A to provide a summary of the unique features of the Flight Control System developed for the X-20 vehicle. This report outlines features developed by the contractor, The Boeing Company, and the FCS subcontractor, Minneapolis-Honeywell Regulator Co., under Contract AF33(657)-7132, and lists the pertinent documents containing design and development details. The features described, the authors believe, can possibly be applied to advanced flight control systems for future aircraft.

ABSTRACT

This report attempts to provide continuity and rationale to the development of the Flight Control System for the X-20 (Dyna-Soar) Vehicle. The unique features are noted and the documents providing details of these features are referenced. The more significant problems encountered in the development are discussed together with the solution or the approaches being taken to obtain a solution.

This technical documentary report has been reviewed and is approved.

Wm E Lamar

WILLIAM E. LAMAR
Director X-20 Engineering Office
Deputy For Systems Engineering

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INTRODUCTION

At the time that the X-20 Program was terminated and the work in progress was being phased out, it became apparent that much useful information had been obtained that should be made available for future programs. Information concerning the X-20 Flight Control System (FCS) was considered especially important since this system was an advanced development involving several unique features.

Among the unique features employed in the FCS were the completely "fly-by-wire" techniques wherein all signals to or from the FCS computer were electrical. In other words, all pilot control signals and all signals to the aerodynamic, thrust vector, and reaction controls were electrical. Another unique feature pertains to the manner that stability was provided to an aerodynamically unstable configuration consisting of the glider and abort rocket. This was accomplished by means of simultaneous aerodynamic and thrust vector control.

The FCS employed dual and triple redundancy to attain a high order of reliability. Redundancy was also carried out, as far as practical, in the electrical connectors, isolation of electrical wiring bundles, electrical circuit mechanical isolation, and environmental isolation by careful orientation of mechanically sensitive components.

A significant number of unique features were incorporated in the Flight Control Subsystem Electronics (FCSE) also, based upon requirements of other subsystems that could be met most effectively by electronic techniques. The Flight Control Subsystem Electronics was procured from the Minneapolis-Honeywell Regulator Company, Minneapolis, Minnesota under a subcontract with The Boeing Company, the prime contractor.

GENERAL DESCRIPTION OF THE X-20 FCS

The X-20 Flight Control System was designed to satisfy attitude control and stability requirements throughout the hypersonic-subsonic flight regime for the glider and glider/transition (abort) configurations. The FCS was designed to operate at dynamic pressures (q) ranging between approximately 0 to 1000 pounds per square foot. Some FCS components, namely the servoactuators and associated signal wiring, had to operate in areas of high environmental heating. The design concept provided temperature control to insure satisfactory operation of these components. Temperature control was provided by insulating the hardware and wiring and providing a constant flow of hydraulic fluid to carry away the heat that passed through the insulation.

A schematic of the X-20 FCS is shown in Figure 1. Control inputs to the FCS are of two types, the manual (human pilot controls) and automatic (preprogrammed or guidance equation controls). The FCSE serves as the "nerve" center for stability and control functions and acts upon the signals by carrying out tasks of signal summation, shaping, gain changing, sensing, etc. The FCSE provides stability and control signals to three types of attitude

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moment-producing devices; these devices deflect aerodynamic surfaces, vector abort rocket thrust, and control thrust from reaction controls. The glider hydraulic system supplies power for the hydraulically operated aerodynamic controls. The hydraulic control energy for the abort rocket thrust vectoring is self-contained since total requirements are small. The glider reaction controls are supplied by fuel contained in the glider. All control and feedback signals (where applicable) involved in X-20 flight control are electrical. In other words, all X-20 stability and control was accomplished on a "fly-by-wire" basis.

The electronic and electro-mechanical equipment comprising the FCSE is shown in Figure 2. The accelerometer package contains dual redundant normal and lateral accelerometers. These accelerometers provide signals for load factor limiting and turn coordination, respectively.

The mode selector enables the pilot to select the mode of control, i.e., manual or automatic. Several submodes of flight control are optional in the manual mode and these are now discussed in order of decreasing sophistication. The most sophisticated submode provides "self-adaptive augmentation". The next is the "fixed gain" submode, wherein the pilot selects one of three values of gain based upon the flight regime; the augmentation configuration for this submode is essentially the same as for the self-adaptive submode except that gain results are less optimum. The manual direct submode, as the name implies, allows direct control of all attitude moment-producing devices by the most direct use of FCS equipment; no augmentation of any type is provided. For example, aerodynamic control surfaces are deflected in proportion to the pilot's control deflections. In manual operation, the various submodes may be selected independently in each of the three control axes. In automatic operation, only the self-adaptive augmentation mode may be used for all axes.

The computer is an analog electronic-electromechanical assembly that accomplishes a myriad of tasks. The mechanization (see Figures 3 and 4) can be described as employing solid state elements, dual and triple redundancy, and integral test-point circuitry. The computer performs all the tasks normally associated with stability and control and a few that are not normally associated with this function. To illustrate the unusual, compensation filter circuitry was employed in aerodynamic surface servo amplifier circuitry to provide assured servoactuator stability margins.

Three gyro packages are included, one for each axis, to provide attitude rate feedback. The prototype of the gyro packages is shown in Figure 5.

All aerodynamic surface trim functions are performed by the trim selector, which was designed with several unusual aspects. All trim functions were accomplished by means of electrical signals. Limited authority was employed in yaw and roll trim to minimize concern about "runaway" trim. Considerable pitch trim authority was needed, however, so provisions were made for disengaging and overriding this signal. To keep glider weight to a minimum and to provide the necessary stability for special instances, a multi-neutral position of the rudders was required. The pilot could select the appropriate neutral rudder position with the rudder position switch.

The equipment shown in Figure 2 was located in the X-20 crew station. Consequently, these items would be exposed to only a comparatively narrow range of pressure and temperature environments. These items were "hard mounted" to the structure, however, which increased the problems of vibration and shock.

REQUIREMENTS

BASIC REQUIREMENTS

Initial requirements for the X-20 FCS were based upon the applicable portions of MIL-F-9490B. (See Appendix for pertinent data relative to referenced reports.) It was apparent at the time that requirements were being established that MIL-F-9490B was not sufficient for space vehicle application. Air Force requirements for the Flight Control System were subsequently defined in ASNR 62-4, ASNR 62-18, Exhibit 620A-60-14A, and Exhibit 620A-61-28.

Contractor documents D2-80600 (Detail Specification) and D2-7483-1 (FCSE Design Specification), specified the detail design requirements and performance of the FCS. The Flight Control System subcontract procurement was based upon the requirements of the D2-7483 series of contractor documents.

During the "Dyna-Soar, Model 620A, Step 1, Mockup Inspection," SPO personnel generated significant design requirements. These requirements pertained primarily to the preservation of physical redundancy in the Flight Control System design. Many requirements for the signals had been established during the course of the program that were extraneous to the system mission. For example, an elevon position signal was used for checkout, pilot display, and recording, in addition to its primary function of feedback. With an all-electrical system, such applications can, in effect, eliminate system redundancy unless proper isolation techniques are used. The SPO, therefore, developed criteria and requirements for isolating the FCS circuits during the course of the program.

CONFIGURATION DEFINITION AND PERFORMANCE REQUIREMENTS

The contractor defined the initial FCS configuration in D2-6909 (Appendix, Sec 1, Item 2), which was subsequently reviewed and approved by the SPO. In the initial FCS configuration, a single hydraulic system was proposed for aerodynamic controls. Although dual first- and second-stage hydraulic servos were proposed, SPO engineering personnel considered that relying upon a single hydraulic system for flight control was unacceptable. After considerable study by both SPO and contractor personnel, the dual hydraulic system was adopted (see Figure 6).

A number of X-20 glider configurations were studied and analyzed. Different configurations required various degrees of relative complexity in the FCS mechanization. Perhaps the most complex FCS mechanization would have resulted from the Model 2035 glider; the final model, the 2050, was considerably simplified.

The contractor's work in establishing FCS performance requirements is reported in D2-8129 and the various revisions. In turn, the long-range performance and design requirements were incorporated into D2-7483-1, the FCSE procurement specification. The data reflected in many of the reports in the appendix (example D2-8083) were utilized in defining FCS performance requirements.

UNIQUE FEATURES

The FCS employed "fly-by-wire" techniques exclusively. These techniques were extended to the projected Pilot In the Booster Loop (PIBOL), which involves an interface between the glider pilot controls and the flight control system of the Titan III booster. It could be said that this was a "fly-by-hot-wire" technique, since a comparatively high temperature environment existed for a number of critical wires between the FCSE computer and the aerodynamic control servoactuators. Insulation and circulating hydraulic fluid were used to reduce the maximum temperature of 1800°F to 450°F for the flight control system wiring outside the crew compartment.

Normal acceleration or load-factor limiting was employed in a somewhat unique manner. Essentially, normal acceleration was limited as a function of velocity. However, the required normal load-factor limit was established on the basis of other limitations in addition to the actual structural capability at particular velocities. (Details of this problem are discussed in D2-8129).

Considerable attention was given to establishing the highest practical reliability. A mean time before failure (MTBF) of 50,000 hours was established for the FCSE augmented mode early in the program. At the time of termination, predictions of MTBF were considerably above this value (80,000 hours). The high predicted FCSE reliability was obtained by a combination of dual and triple redundancy techniques (see Figure 7).

A unique self-adaptive gain logic technique was developed after it was discovered during a simulated approach and landing program that the pilot's control activity during turbulence reduced the self-adaptive gain sufficiently to produce poor handling characteristics. The flight simulation was accomplished in an NF-101A aircraft in which a prototype Minneapolis-Honeywell MH-90X FCSE was installed with modifications to simulate the MH-132 or X-20 FCSE. The "logic" and self-adaptive pass band utilized in the MH-90 allowed energy from the turbulence and pilot control activity spectrum to interfere with the computation of the normal self-adaptive gain. Although this adverse phenomenon occurred only during conditions of unusual turbulence, it was decided that this feature must be improved. The final report, Minneapolis Honeywell 2731-TR1, covers the NF-101A flight test program in detail and the two versions of the self-adaptive gain computer are described technically in D2-8129 and D2-8083. The revised gain computer was subjected to wide spectra of simulated turbulence and pilot control frequency inputs in ground-based simulation testing. In essence, all aspects of the revised self-adaptive gain computer appeared to be satisfactory at termination. A flight test program was planned but was not conducted on the revised gain computer.

The malfunction detection system for the hydraulic servo in the aerodynamic surface controls is novel and warrants particular attention for possible future applications. Necessary switching logic was developed that enables the operation of a defective servo valve to be sensed and switched out in time to preclude its exceeding structural limitations. Structural limitation is used in the broad sense and includes the temperature-deflection limitations of the aerodynamic control surfaces. This development is described in D2-8129, the primary reference for servo malfunction detection development.

The FCSE included considerable circuitry that precluded the coupling of the structure and the FCS. While structural "decoupling" circuitry is not unique, the relative "closeness"

of frequencies for critical elements was unique in this application of the self-adaptive flight control technique. The relatively close proximity of the aerodynamic short period frequency, the self-adaptive limit cycle frequency, and the various structural mode frequencies was the subject of considerable analysis. Early analysis resulted in very high order transfer functions for decoupling purposes. Subsequent refinement resulted in some simplification, but the order of the transfer functions was considerably above that used in the X-15 FCS. The various revisions of D2-8129 and D2-8083 show the evolution of "structural compensation".

In addition to the unique application of the side stick controller and "fly-by-wire" techniques, a nonlinear mechanization was designed for the controller and rudder pedals. This mechanization provided both the range and positioning accuracy required for satisfactory piloted control. The nonlinearity was provided by the winding technique used in the redundant electrical transducers on the pilot controls. Details concerning nonlinearity, force-displacement ratios, and other data are covered in detail in documents D2-7483-1, D2-8129, and D2-8083.

The speed brake (secondary flight control) function was uniquely integrated with the primary flight controls by using outboard rudder deflections. The initial X-20 configuration had a separate speed brake surface and consequently the design was relatively straightforward. The design details of the integrated primary-secondary flight controls required careful attention to retain the predicted reliability for primary flight controls. Nonredundancy was permitted in the secondary control function, but a provision was required to enable the pilot to positively disconnect the secondary control function in the event of failure.

The integration of the various attitude moment-producing controls, cross axis signal integration, and cross axis gain scheduling employed in the X-20 FCSE are unique in some aspects. Both the thrust vector and aerodynamic controls were required during operation of the abort rocket to provide the necessary attitude control moments throughout the performance regime. The gain and dynamics for thrust vector deflection were determined for each axis relative to the aerodynamic control requirements. The large range in angle of attack flight capability of the X-20 resulted in considerable inertial and aerodynamic cross coupling. Open loop "decoupling" to improve overall augmented control response was provided by a cross feed and summation of aileron deflection command signals with the yaw axis signals. Gain "slaving" was utilized in the roll axis by using a "percentage" of the yaw axis gain to form the roll gain. This gain "slaving" obviously generated requirements for more complex malfunction detection logic than otherwise would have been necessary.

STATUS OF FCS AT PROJECT TERMINATION

The design of the FCS was essentially complete at the time that the X-20 project was terminated. One set of production FCSE hardware had been fabricated for qualification. The manufacturer was in the process of conducting acceptance checks prior to initiating qualification tests.

The contractor and FCSE subcontractor were using technical laboratory-level hardware for various tests and the contractor was testing the equipment in the Guidance and Control Development Model (G&CDM). The fundamental aspects of integrating the guidance and control hardware had been assured from tests conducted in the G&CDM (see Figure 8).

The G&CDM was an important tool in advancing the development of the complex FCS for the X-20 vehicle. This facility had enabled early detection of unforeseen problems and had provided a means for resolving known problems by testing the actual equipment. Several important problems, including signal scaling, were revealed by tests and had been remedied prior to project termination. The new self-adaptive gain logic had been well checked out in the G&CDM, although it had not been flight tested. At the time of termination, an aircraft was being sought to serve as an FCS test bed to verify the operation of the new gain logic and to provide operational experience so as to establish confidence in the FCSE hardware.

Complete FCSE subsystem developmental flight tests were not planned at program initiation. However, requirements for complete flight tests were established after numerous changes and additions had been made to the FCSE and the pilots had expressed concern about handling qualities in the landing regime. In addition, just prior to termination of the program, the SPO had collected considerable information on the value of FCS flying test bed programs in general, and the requirements for an X-20 FCS flying test bed in particular. Such flights, in addition to providing assurance that the new gain logic was acceptable, could have confirmed or provided information for optimizing some of the more fundamental FCS configuration parameters. These include the "stick gearing" (ratio of the feedback to the command) for both the augmented and the manual direct control modes in the approach and landing regimes.

The subcontractor had completed the FCSE acceptance test requirements, Document R-ED-1382, and Qualification test requirements, Document R-ED-1236. The contractor and the SPO were reviewing these documents at the time of project termination.

An FCS configuration was defined for glider abort at project termination. Document D2-8083 provides abort stability and control analysis information and simulation details. Considerable work remained to be done, however, in terms of defining a satisfactory configuration to perform within the required safety limits.

SIGNIFICANT EVENTS AND MILESTONES

A few of the more significant events and milestones in the development of the flight control system for the X-20 vehicle are identified as follows:

1. Evaluation of proposals, selection of preferred proposal, and recommendations to X-20 SPO management concerning source selection for the X-20 FCSE procurement - September-December 1960.

2. Initial "PERT" conference with the contractor to establish ground rules and initial network in airframe area - December 1960.

3. NASA-X-20 SPO Step I Flight Control Development Conference - August 1961.

4. Step I Mockup Inspection - September 1961.

5. Initiation of Guidance and Control Development Model (G&CDM) Design Activity - December 1961.

6. Initiation of six-degree-of-freedom stability and control simulation utilizing estimated aerodynamic and structural mode data for Model 2050 glider - April 1962.

7. Hydraulic components available for installation in G&CDM - October 1962.

8. Display and associated equipment installed in G&CDM - December 1962.

9. Technical laboratory model FCSE fabrication and checkout tests completed - February 1963.

10. Preliminary lateral and longitudinal aero-servo-elastic studies completed - March 1963.

11. Technical laboratory model FCSE installed in G&CDM - April 1963.

12. Evaluation completed on aero-servo-elastic impact on FCSE design based upon estimated glider structural characteristics for 5-segment Titan III booster - May 1963.

13. Completion of first phase of FCSE and inertial guidance subsystem tests in G&CDM - August 1963.

14. First qualification model FCSE fabricated - November 1963.

15. Second phase of G&CDM testing completed utilizing hydraulic servo actuators - November 1963.

CONCLUSIONS

Several unique features were designed for the X-20 FCS and had been developed to the point that feasibility was demonstrated by means of analysis, simulation, and testing in the G&CDM. Some of these developments could be applicable to other advanced systems. These features are discussed as follows:

1. The state-of-the-art in the area of applying a self-adaptive FCS to a relatively elastic aerodynamic structure was advanced in that a new self-adaptive "gain logic" and more complex structural compensation were developed and ground tested in the X-20 FCSE.

2. The state-of-the-art of "fly-by-wire" flight control systems was advanced by analysis, simulation, ground based testing, and flight tests in an NF-101 aircraft equipped with a sidestick controller and self-adaptive FCS.

3. A design approach has been developed to permit FCS operation in the environmental temperature regime associated with re-entry flight. Although the equipment was not flight proven, the feasibility of the approach is considered to have been demonstrated in the various ground based high-temperature tests of hydraulic and electrical components.

APPENDIX

REFERENCE DOCUMENTS FOR X-20 FCS DEVELOPMENT PROGRAM

The following documents have been selected as those describing the requirements, developments, and features of the FCS for the X-20. They have been arranged in four sections: 1, those prepared by the prime contractor; 2, those prepared by the FCS subcontractor; 3, those prepared by the SPO; and 4, the formal ASD Technical Documentary Reports. Those documents marked with an asterisk are available only from retired records. Those not marked have been released to the Defense Documentation Center, where copies should be available.

SECTION I.

THE BOEING COMPANY REPORTS

1. D2-7438-1 CONFIDENTIAL - Proposed Deviations to DS (Step I) Statement of Work thru June 30 1961*

2. D2-6909 CONFIDENTIAL - Preliminary System Design Report, Preliminary System Analysis and Integration Report and Preliminary System Description of the Dyna-Soar Step I.

3. D2-7483-0 UNCLASSIFIED - Engineering Program Statement X-20 Glider Flight Control Subsystem Electronics*

4. D2-7483-1 CONFIDENTIAL - Glider Flight Control Subsystem Electronics Design Procurement Specification*

5. D2-7483-2 UNCLASSIFIED - Bench Test Equipment, Flight Control Subsystem Electronics, Procurement Specification for Dyna-Soar

6. D2-7483-3 UNCLASSIFIED - Engineering Program Statement, Bench Test Equipment, Flight Control Subsystem Electronics

7. D2-8129 CONFIDENTIAL - Glider Flight Control Subsystem Analysis Report dated 12 September 1961

8. D2-8129 CONFIDENTIAL - Glider Flight Control Subsystem Analysis Report dated 1 July 1963

9. D2-8083 CONFIDENTIAL - Glider Stability and Control Analysis, Model 844-2050

10. D2-80065 CONFIDENTIAL - Aerodynamic Stability and Control, Vols I & II

11. D2-8080-1 CONFIDENTIAL - Glider Performance Characteristics Report

12. D2-8080-2 CONFIDENTIAL - Air Vehicle Performance Characteristics Report

13. D2-80762 CONFIDENTIAL - Pilot In The Booster Control Loop Study - Final Report (Volume I)*

14. D2-80762 CONFIDENTIAL - Pilot In The Booster Control Loop Study - Final Report (Volume II)*

15. D2-6909-1 CONFIDENTIAL - Interim System Description of the Dyna-Soar Step I*

16. D2-6909-2 CONFIDENTIAL - System Description of Dyna-Soar*

17. D2-80600 CONFIDENTIAL - Detail Specification Glider/Transition Section

18. 10-81007 UNCLASSIFIED - Valve Assembly, Hydraulic, Glider Control Surface*

19. 10-81157 UNCLASSIFIED - Rudder Brake Control Assembly*

20. D2-7481 UNCLASSIFIED - Electronics Packaging Requirements Contract Procured Flight Equipment*

21. D2-8131-3 CONFIDENTIAL - Secondary Power Analysis - Hydraulic Power Subsystem*

22. 10-81014 UNCLASSIFIED - Hydraulic Power Supply, Servo Actuator, and Thrust Vectoring Control System*

23. 10-81135 CONFIDENTIAL - Reaction Control System - Hydrogen Peroxide

24. Dyna-Soar Model 620A Step I Mockup Inspection September 11-15 and 18-20 1961 (one unclassified and one classified report)*

SECTION 2.

MINNEAPOLIS-HONEYWELL REGULATOR COMPANY REPORTS

1. R-ED-1382 UNCLASSIFIED - Acceptance Test Requirements for the YG368A-1 Flight Control Subsystem*

2. R-ED-1236 UNCLASSIFIED - Qualification Test Requirements for the YG368A1A (Qualification) Flight Control Subsystem Electronics*

3. 2 2546-TR15 CONFIDENTIAL - Volume II Final Analysis Report of the X-20 Flight Control Subsystem*

4. 2731-TR1 UNCLASSIFIED - Final Report, Approach and Landing Investigation Side Stick Controller*

SECTION 3.

X-20 SPO DOCUMENTS

1. ASNR 62-4 CONFIDENTIAL - Tab A - Dyna-Soar System Specification Glider/ Transition Section

2. ASNR 62-18 UNCLASSIFIED - Dyna-Soar System Specification Preliminary Flight Rating Tests for Glider/Transition Section, Subsystems, Components or Units

3. ASNR 62-10(A) UNCLASSIFIED - X-20 Dyna-Soar Master Data Measurements List

4. Exhibit 620A-60-14A CONFIDENTIAL - Statement of Work System 620A Dyna-Soar (Step I) (Period 27 April 1960 thru 30 June 1961) for Contract AF33(600)-41517, 6 August 1960, Revised 1 November 1960

5. Exhibit 620A-61-28 CONFIDENTIAL - Statement of Work System 620A Dyna-Soar (Step I) (Period October 1961 thru Completion)

SECTION 4.

ASD TECHNICAL DOCUMENTARY REPORTS

1. ASD-TDR-63-148 CONFIDENTIAL - Volume I Proceedings of 1962 X-20A (Dyna-Soar) Symposium-General, Testing and Ground Support and Subsystems.

2. ASD-TDR-63-148 CONFIDENTIAL - Volume II Proceedings of 1962 X-20A (Dyna-Soar) Symposium - Flight Mechanics and Guidance.

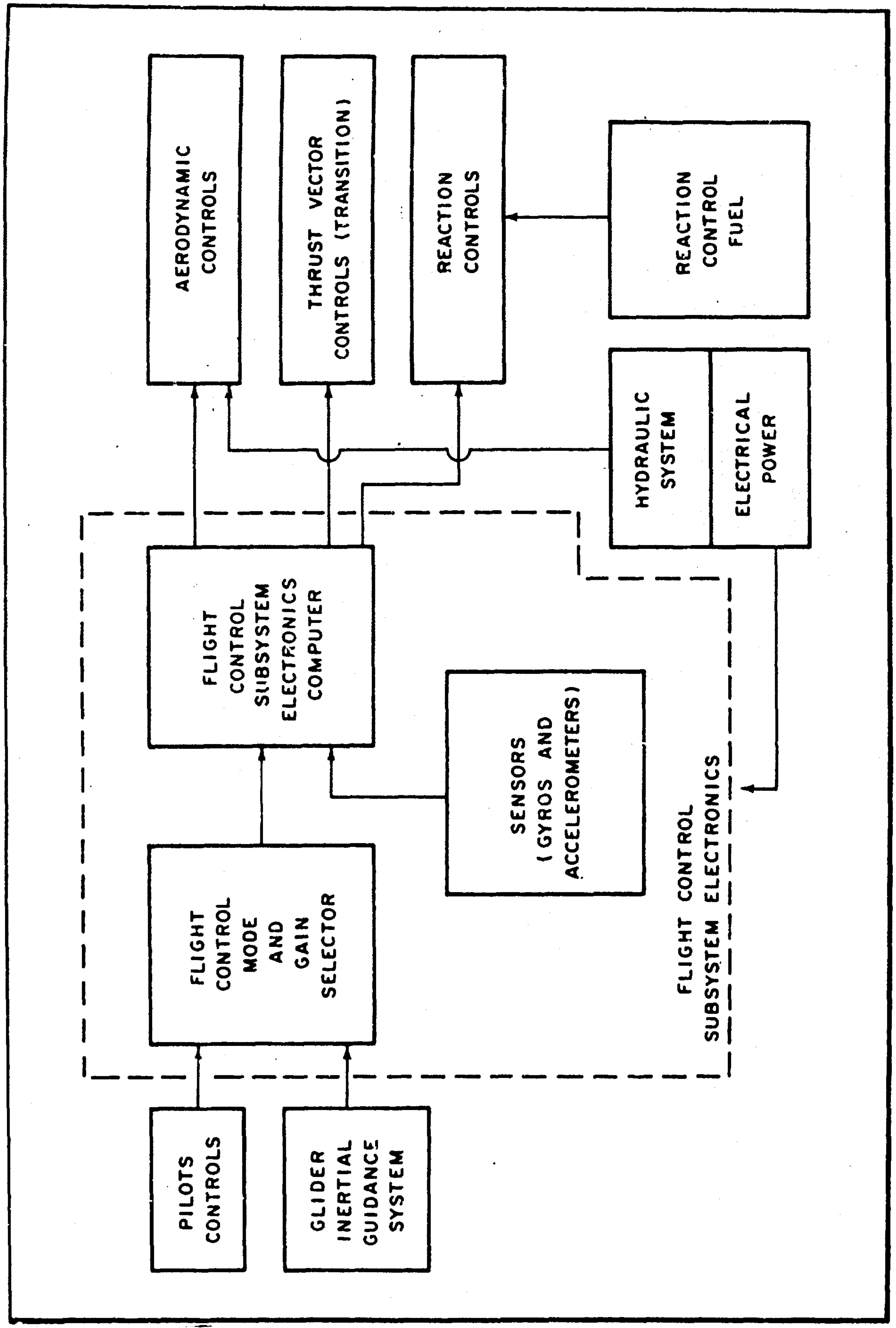

Figure 1. X-20 Dyna-Soar Glider Flight Control System Block Diagram

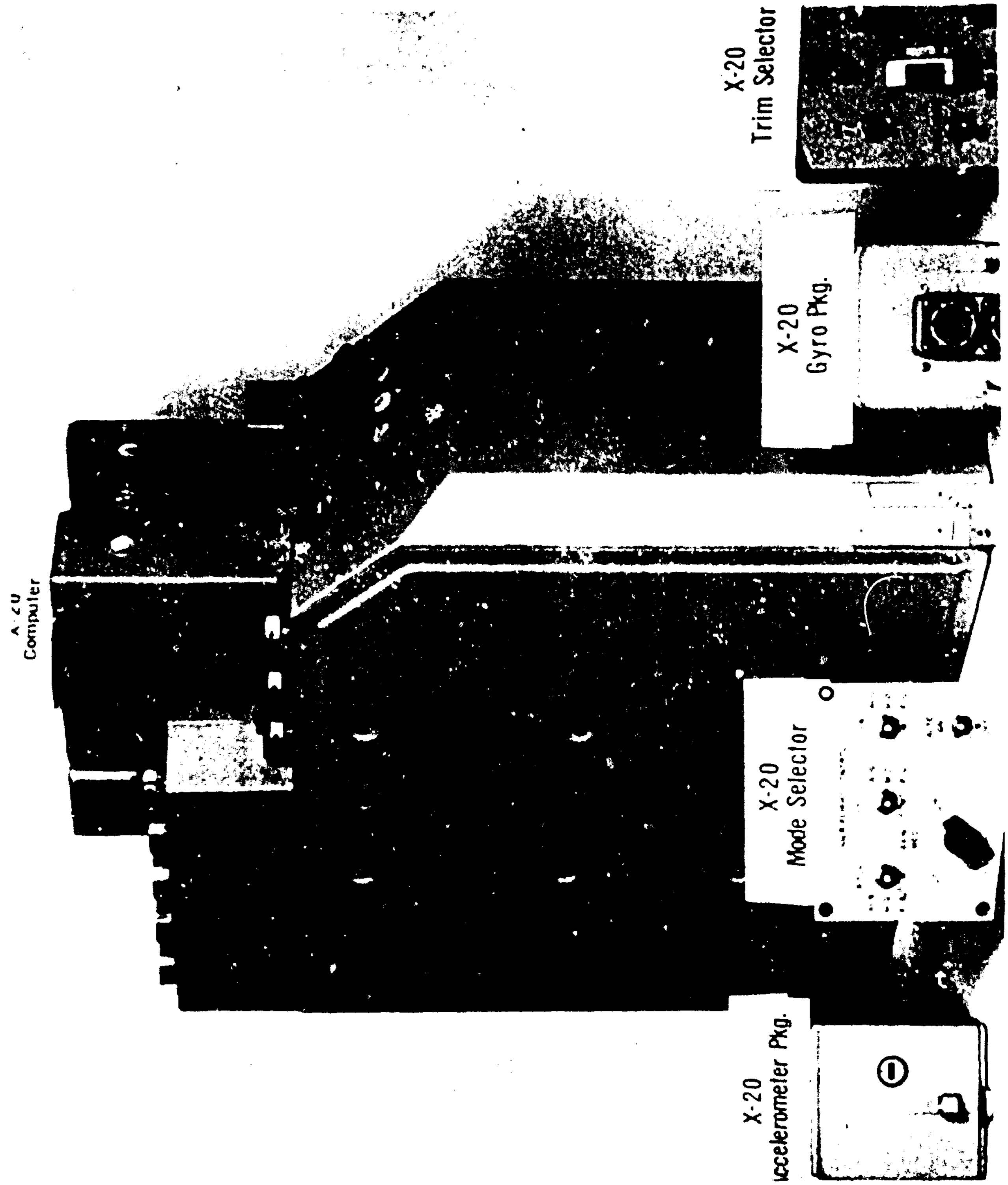

Figure 2. X-20 Flight Control Subsystem Electronics Components

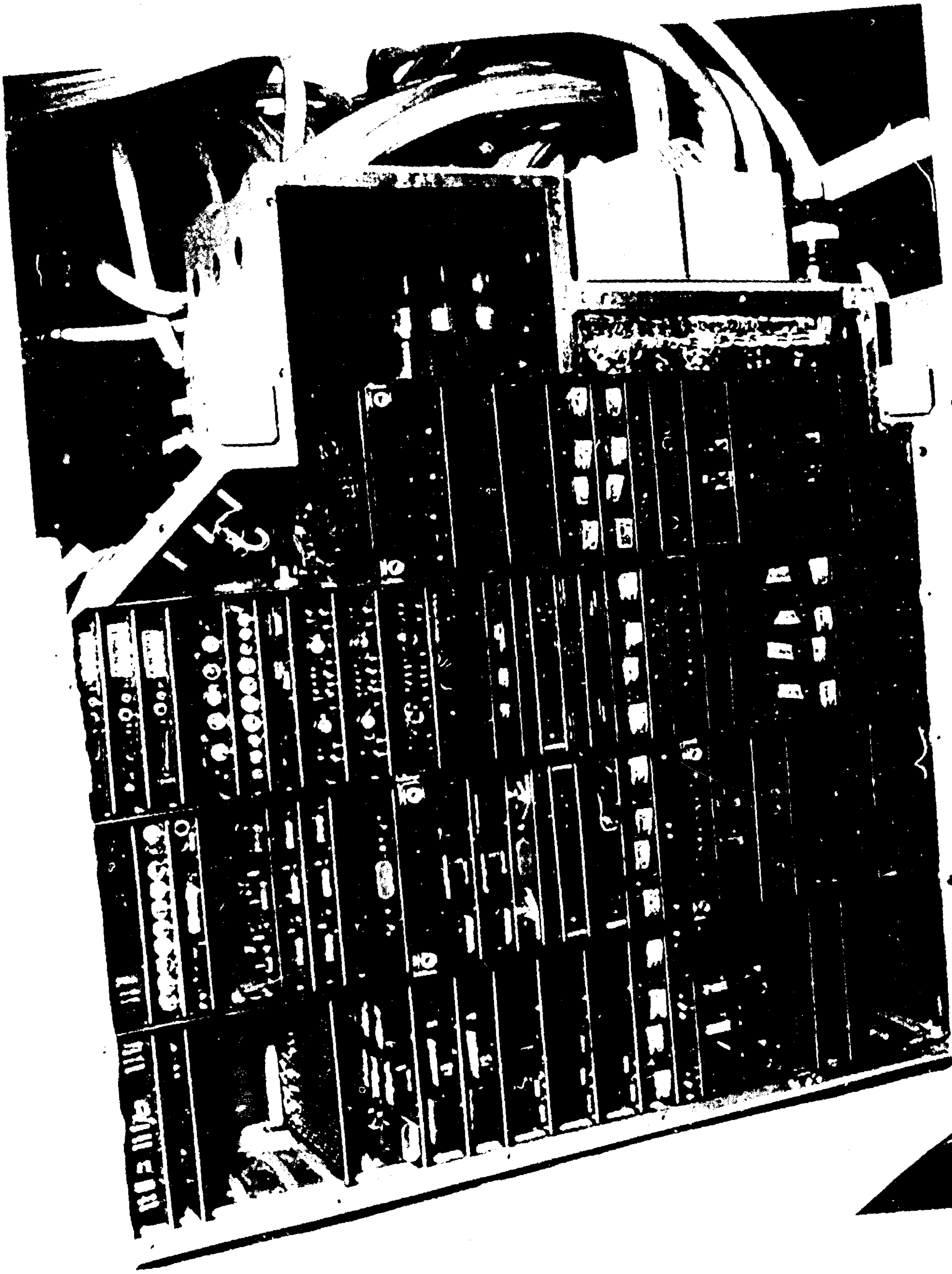

Figure 3. Flight Control Subsystem Electronics Computer (Cover Removed) Showing Card Access Side

Figure 4. Flight Control Subsystem Electronics Computer (Cover Removed) Showing Wiring Harness

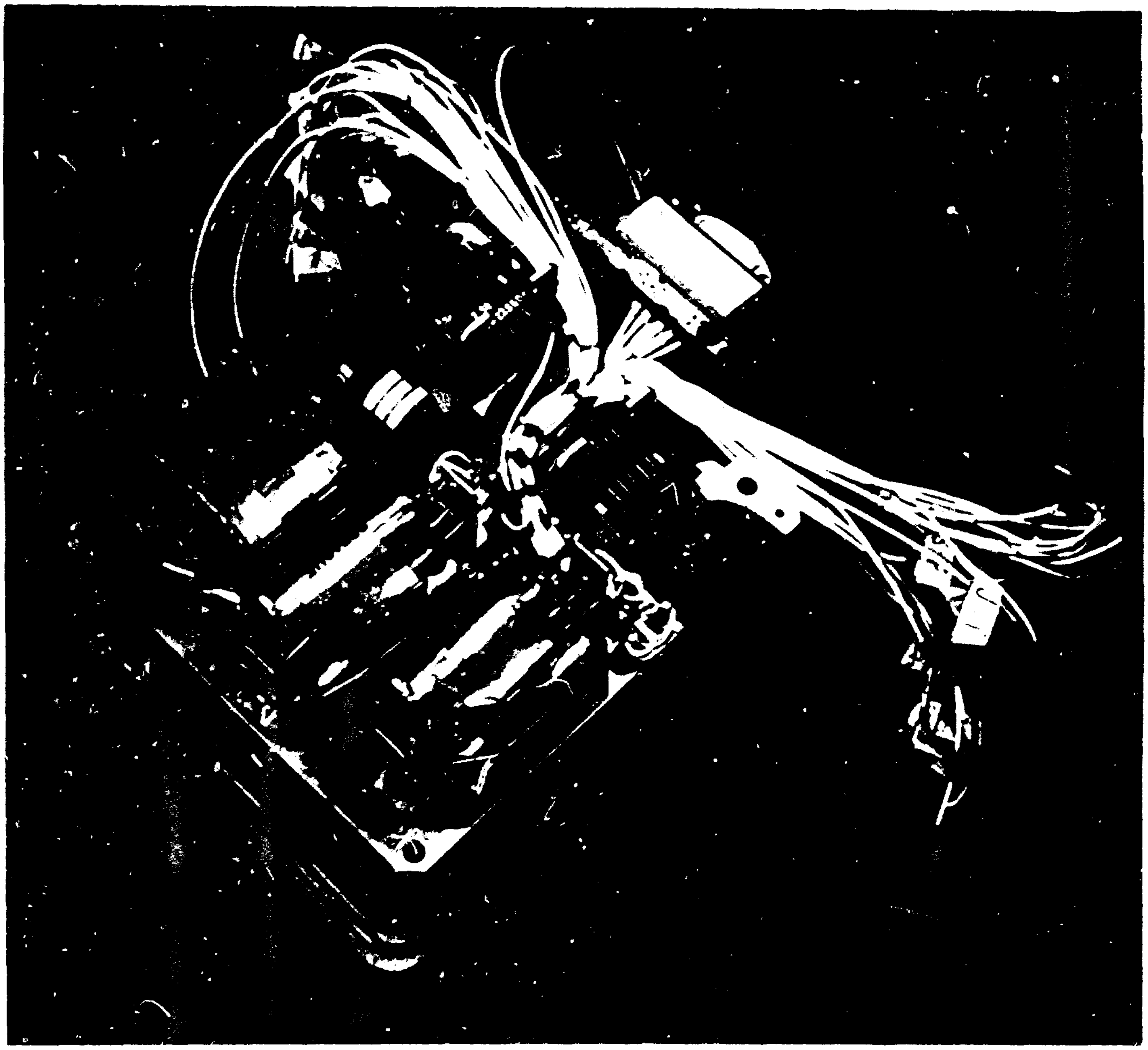

Figure 5. Prototype of Flight Control Subsystem Electronics Gyro Package (Cover Removed)

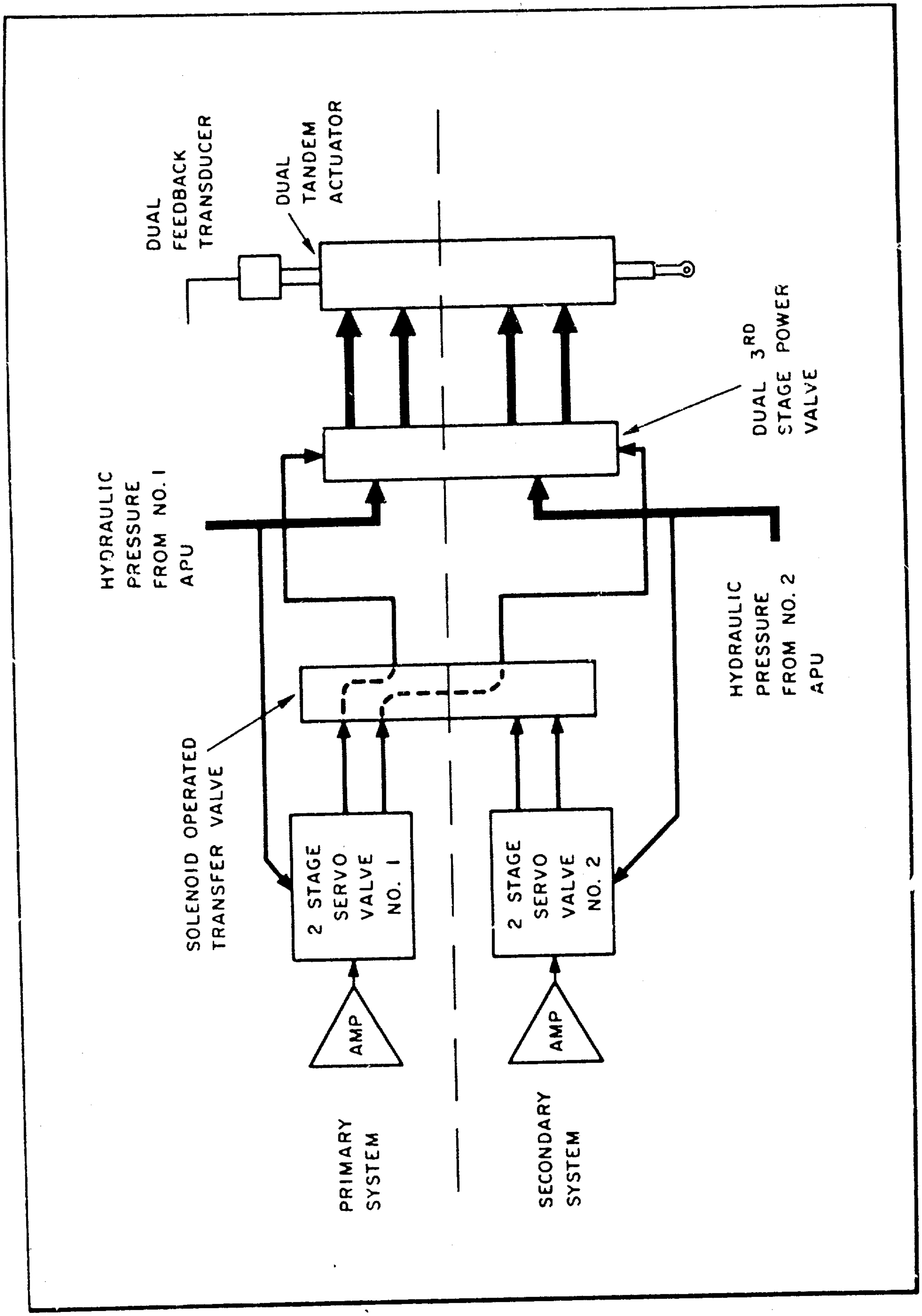

Figure 6. Typical Control Surface Dual Hydraulic Servo Loop

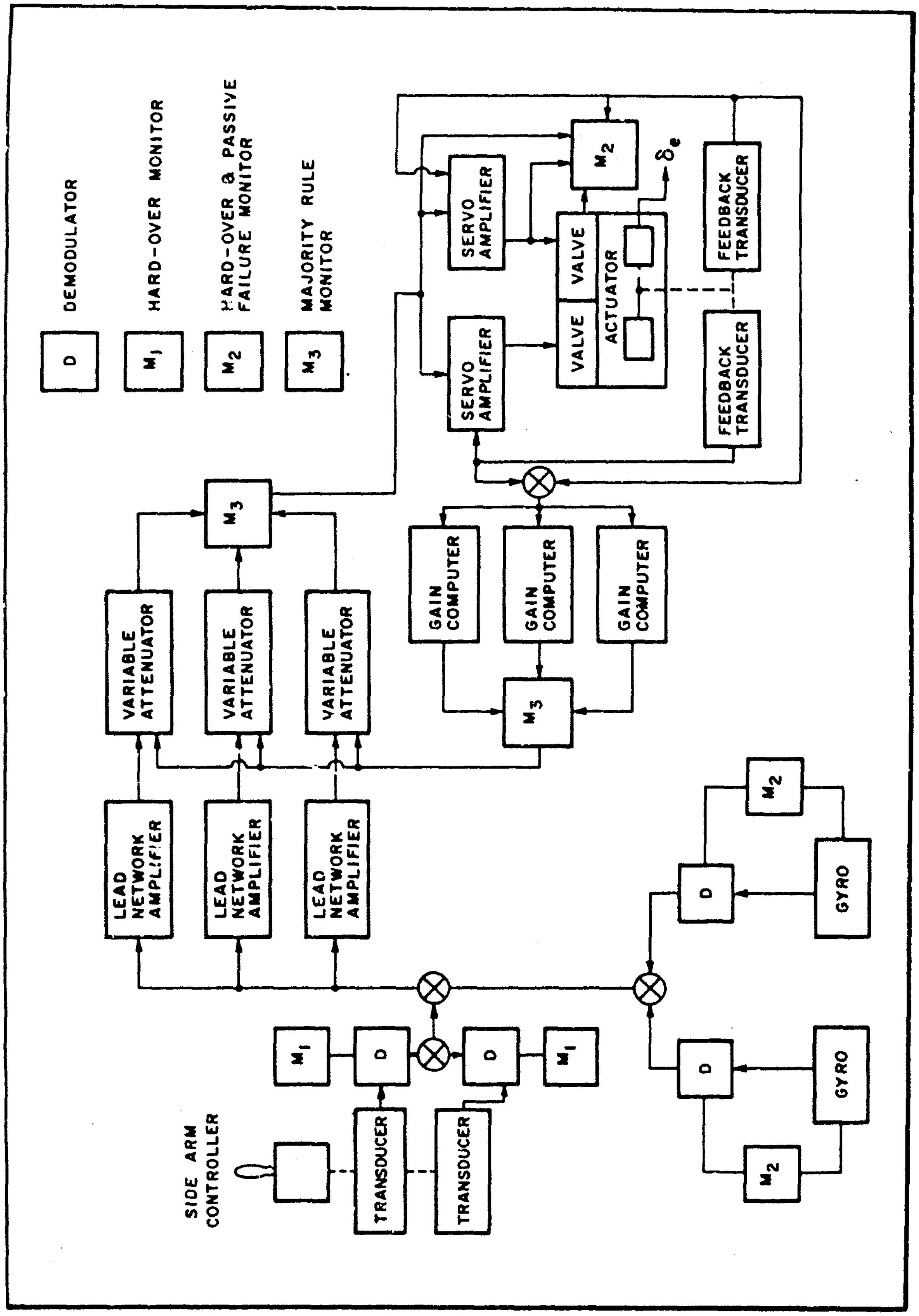

Figure 7. Redundancy Technique, Adaptive Control System, Pitch Axis

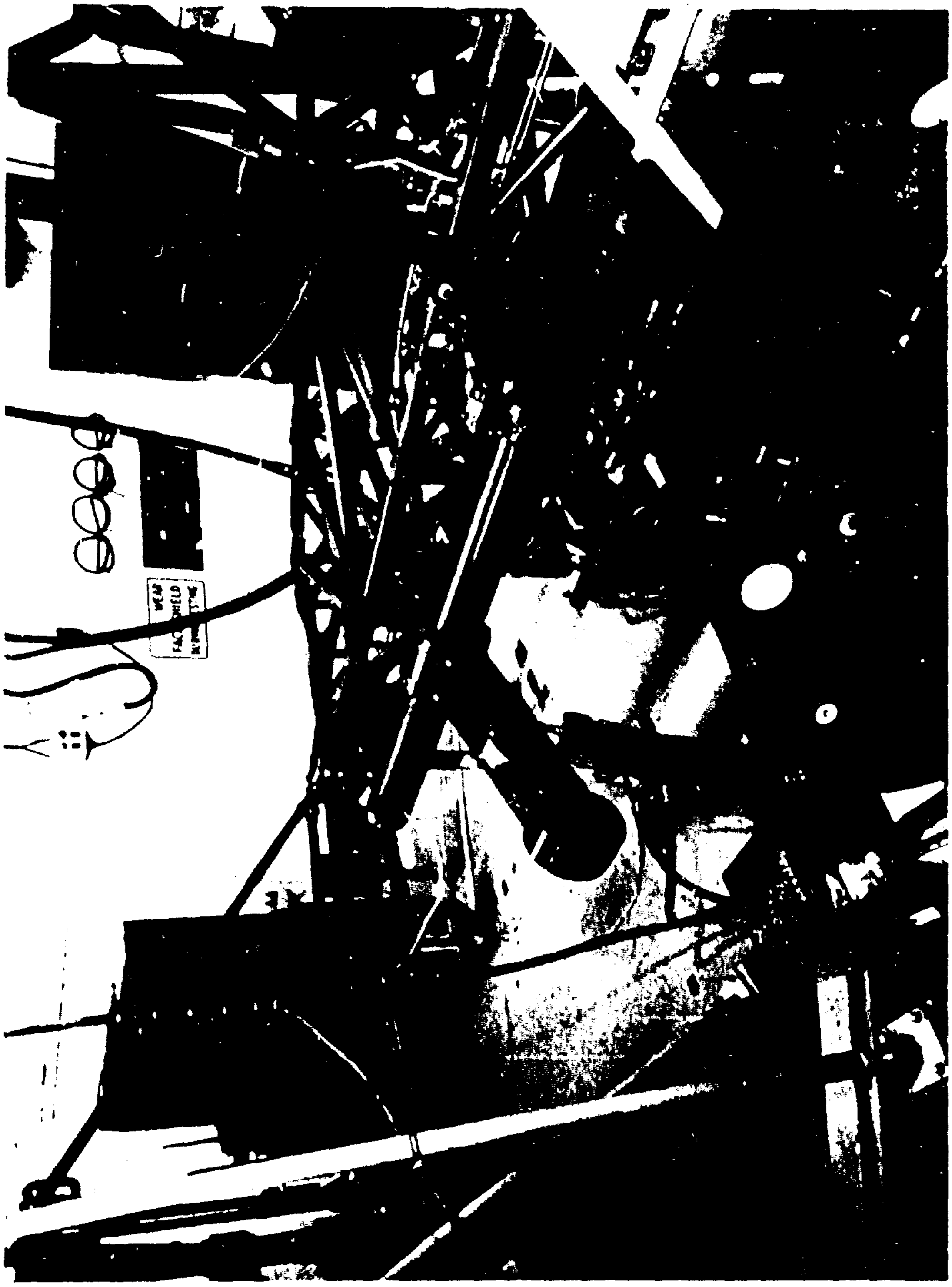

Figure 8. Portion of Guidance and Control Development Model Simulated Structure and Loading Devices